ECE 371
Materials and Devices

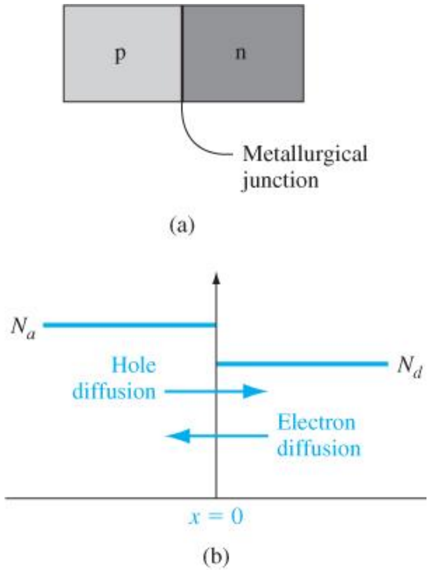
11/05/19 - Lecture 19

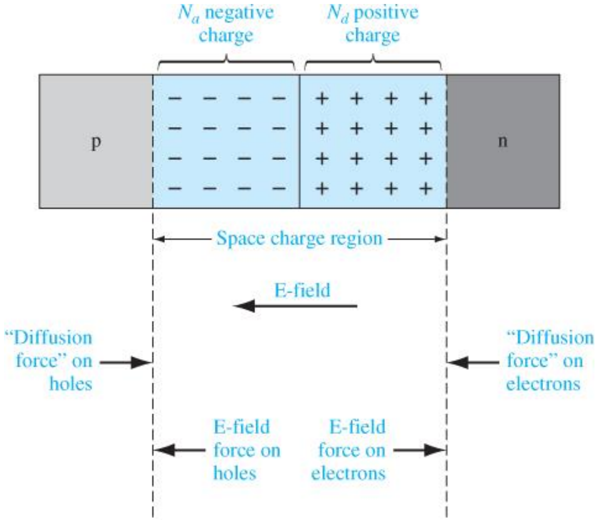
PN Junction, Built-In Potential, Built-In Electric Field, Space Charge Width

General Information

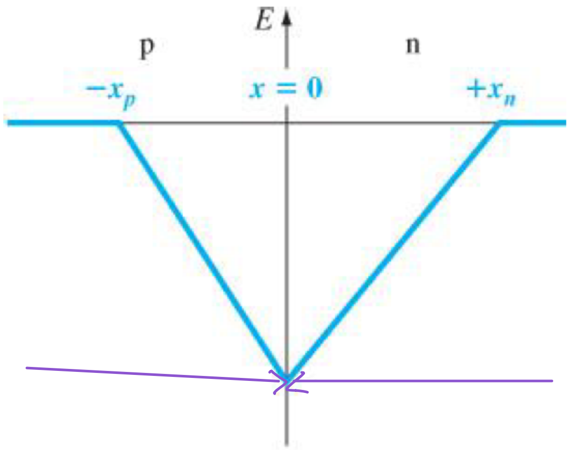
- Homework 6 assigned and due 11/07
- We will *try* to return midterm #2 by Thursday
- Reading for next time: 7.3 and 7.4

pn Junction - Basics





- Majority carriers diffuse to the opposite side and become minority carriers where they recombine
- Diffusion current is balanced by drift current
- Depletion approximation is assumed (step-like junction)
- Doping on the n and p sides is assumed to be uniform
- In the space charge (depletion) region electrons and holes are swept out by the electric field



$-\dfrac{eN_a x_p}{\epsilon_s}$

max value that E-field has

$\dfrac{-eN_d x_n}{\epsilon_s}$

Figure 7.5 | Electric field in the space charge region of a uniformly doped pn junction.

Built-in E-field expressions

for p side

$$E(x) = \frac{eN_a}{\epsilon_s}(x_p + x)$$

for n side

$$E(x) = \frac{eN_d}{\epsilon_s}(x_n - x)$$

$$N_a x_p = N_d x_n$$

pn Junction – Built in Potential

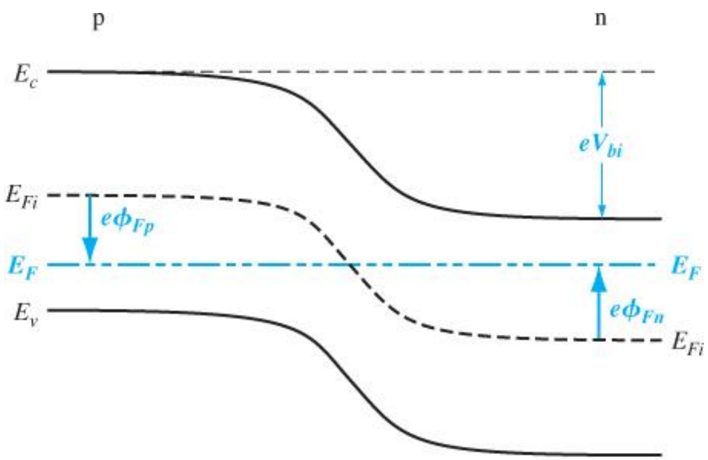


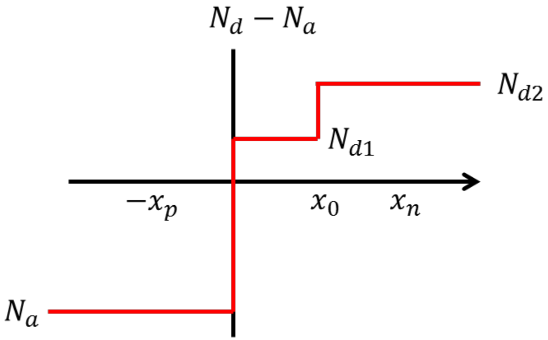
Figure 7.3 | Energy-band diagram of a pn junction in thermal equilibrium.

$$\boxed{V_{bi} = \frac{kT}{e} ln\left(\frac{N_d N_a}{n_i^2}\right)}$$

- A potential barrier forms across the junction for holes moving left to right and electrons moving right to left
- N_a and N_d now refer to the total net impurity concentration on either side of the junction
- The built-in potential varies with the doping concentrations, but only slightly
- V_{bi} for silicon is ~ 0.7 V
- For very high doping, V_{bi} is approximately E_g/e

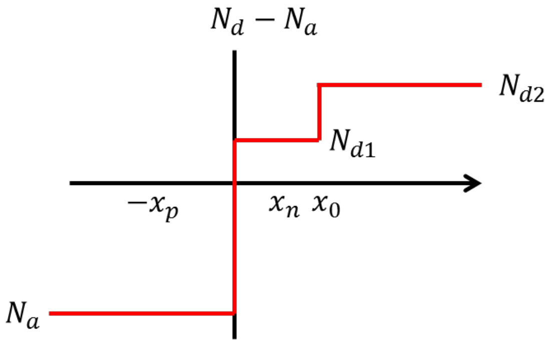
Additional Notes on V_{bi}

- V_{bi} equation is valid for non-degenerate semiconductors only since it was derived using Boltzmann approximation
- For a multi-step junction, V_{bi} only depends upon the doping concentrations at the edges of the space charge region on each side (i.e. – at $-x_p$ and x_n)



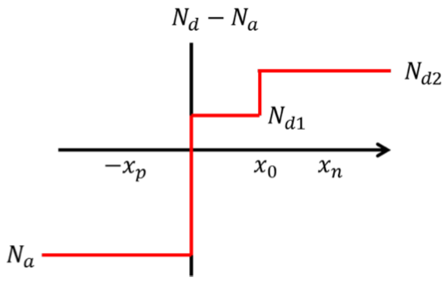
$\rightarrow$

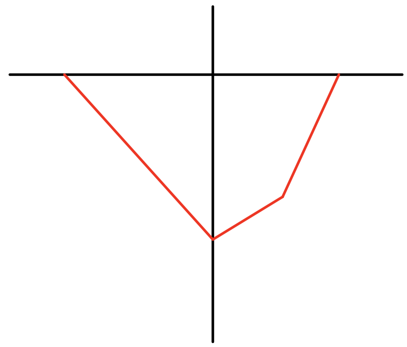
$$\boxed{V_{bi} = \frac{kT}{e} ln\left(\frac{N_{d2}N_a}{n_i^2}\right)}$$ $x_n > x_0$

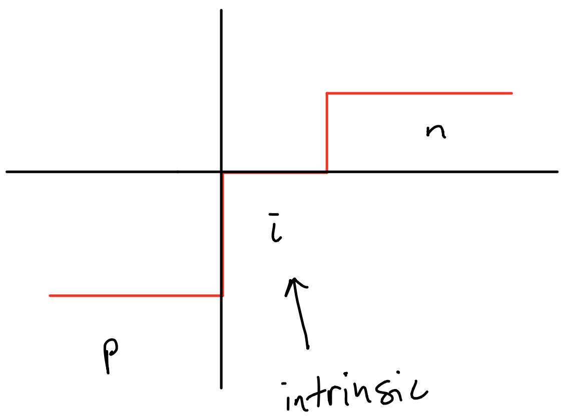


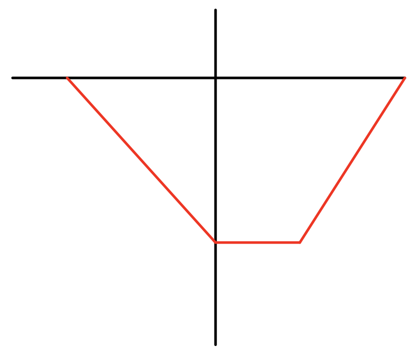
$\rightarrow$

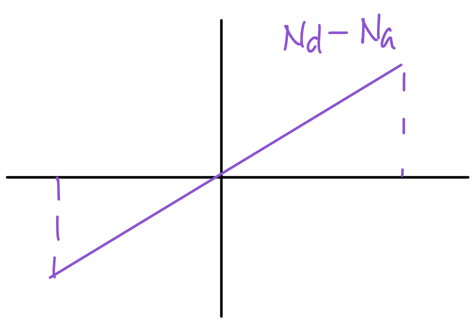
$$\boxed{V_{bi} = \frac{kT}{e} ln\left(\frac{N_{d1}N_a}{n_i^2}\right)}$$ $x_n < x_0$











$\longrightarrow$ parabolic

Nd - Na $\longrightarrow$ $\rho(x)$ charge density

$\rho(x)$ $\longrightarrow$ $E(x)$ e field

$E(x)$ $\longrightarrow$ $\phi(x)$ density

$\phi(x)$ $\longrightarrow$ V_{bi} $\longrightarrow$ energy band

Example 7.1

Objective: Calculate the built-in potential barrier in a pn junction.

EXAMPLE 7.1

Consider a silicon pn junction at $T = 300$ K with doping concentrations of $N_a = 2 \times 10^{17}$ cm^{-3} and $N_d = 10^{15}$ cm^{-3}.

■ **Solution**

The built-in potential barrier is determined from Equation (7.10) as

$$V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right) = (0.0259) \ln\left[\frac{(2 \times 10^{17})(10^{15})}{(1.5 \times 10^{10})^2}\right] = 0.713 \text{ V}$$

If we change the doping concentration in the p region of the pn junction such that the doping concentrations become $N_a = 10^{16}$ cm^{-3} and $N_d = 10^{15}$ cm^{-3}, then the built-in potential barrier becomes $V_{bi} = 0.635$ V.

■ **Comment**

The built-in potential barrier changes only slightly as the doping concentrations change by orders of magnitude because of the logarithmic dependence.

Built-In Electric Field

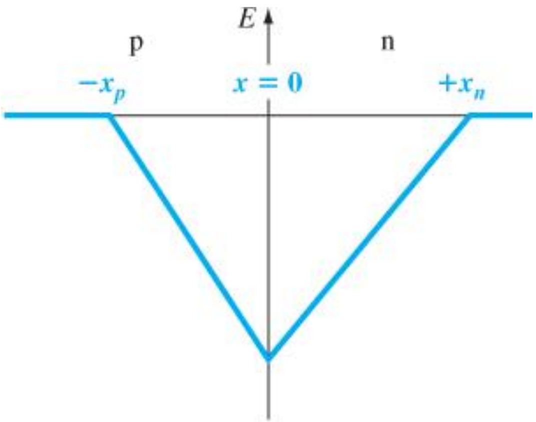


Figure 7.5 | Electric field in the space charge region of a uniformly doped pn junction.

- Built-in electric field is present even without an applied bias
- E-field is negative since it points in the –x direction
- Maximum magnitude of E-field occurs at the junction

$$E(x) = \frac{-eN_a}{\varepsilon_s}(x + x_p) \text{ for } -x_p \le x \le 0$$

$$E(x) = \frac{-eN_d}{\varepsilon_s}(x_n - x) \text{ for } 0 \le x \le x_n$$

$$N_a x_p = N_d x_n$$

# of charges per area on the n and p sides are equal

Built-In Potential

$V_{bi} = \phi(x = x_n)$

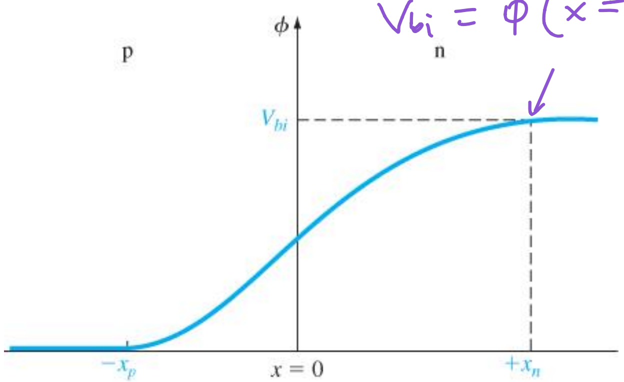
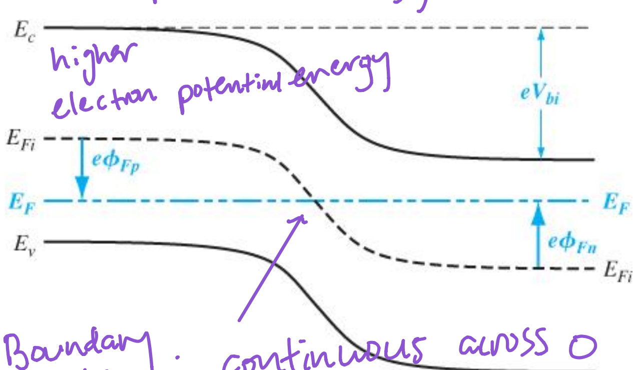


Figure 7.6 | Electric potential through the space charge region of a uniformly doped pn junction.

potential energy diagram



higher electron potential energy

Boundary condition: continuous across 0

- Quadratic dependence of potential on distance
- Plot applicable to electrons and holes
- Holes:
  - Lower potential on the p-side
  - Lower potential energy on the p-side
- Electrons:
  - Lower potential on the p-side
  - Lower potential energy on the n-side
- Built-in potential causes "diode" behavior – blocks current at zero bias

derived from $\phi(x) = -\int E(x)dx$

$$\boxed{V_{bi} = \frac{e}{2\varepsilon_s}\left(N_d x_n^2 + N_a x_p^2\right)}$$ 7.26

2 ways to represent V_{bi}

$$\boxed{V_{bi} = \frac{kT}{e} ln\left(\frac{N_d N_a}{n_i^2}\right)}$$

$$\boxed{V_{bi} = \frac{e}{2\varepsilon_s}\left(N_d x_n^2 + N_a x_p^2\right)}$$

Depletion Width

$$N_a x_p = N_d x_n \longrightarrow x_p = \frac{N_d}{N_a} x_n$$

$$V_{bi} = \frac{e}{2\epsilon_s}\left[N_d x_n^2 + N_a x_p^2\right]$$

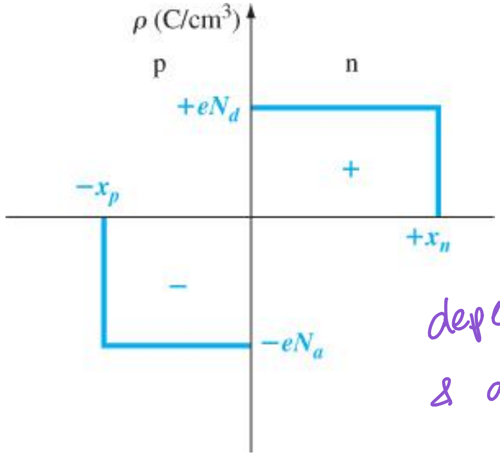
$$\downarrow$$

$$x_n = \left[\frac{2\epsilon_s V_{bi}}{e}\left(\frac{N_a}{N_d}\right)\frac{1}{(N_a + N_d)}\right]^{1/2}$$

space charge width on n-side

x_p can be derived the same way

Depletion ~~Space Charge~~ Width



depends on Vbi
& doping levels

- Depletion splits between the n and p sides and the splitting ratio depends upon the doping
- For an asymmetric junction, most of the space charge width occurs on the lightly doped side
- Total charge on each side must be equal ($N_a x_p = N_d x_n$)

space charge width on n side

$$\boxed{x_n = \left[\frac{2\varepsilon_s V_{bi}}{e}\left(\frac{N_a}{N_d}\right)\frac{1}{N_a + N_d}\right]^{\frac{1}{2}}}$$

space charge width on p side

$$\boxed{x_p = \left[\frac{2\varepsilon_s V_{bi}}{e}\left(\frac{N_d}{N_a}\right)\frac{1}{N_a + N_d}\right]^{\frac{1}{2}}}$$

total space charge width

$$\boxed{W = x_n + x_p = \left[\frac{2\varepsilon_s V_{bi}}{e}\frac{N_a + N_d}{N_a N_d}\right]^{\frac{1}{2}}}$$

check x_n $\rightarrow$ if $N_a >> N_d$

$$x_n = \left[\frac{2\epsilon_s V_{bi}}{e} \frac{1}{N_d}\right]^{1/2}$$

check x_p $\rightarrow$ if $N_d >> N_a$

$$x_p = \left[\frac{2\epsilon_s V_{bi}}{e} \frac{1}{N_a}\right]^{1/2}$$

$$x_p = \left[\frac{2\varepsilon_s V_{bi}}{e}\left(\frac{N_d}{N_a}\right)\frac{1}{N_a + N_d}\right]^{\frac{1}{2}}$$

$N_d = 1e17$ $N_a = 1e15$

$$\frac{N_d}{N_a} = 100 \qquad \frac{1}{1e17}$$

Test Your Understanding 7.1

TYU 7.1 Calculate V_{bi}, x_n, x_p, W, and $|E_{max}|$ for a silicon pn junction at zero bias and $T = 300$ K for doping concentrations of (*a*) $N_a = 2 \times 10^{17}$ cm^{-3}, $N_d = 10^{16}$ cm^{-3} and (*b*) $N_a = 4 \times 10^{15}$ cm^{-3}, $N_d = 3 \times 10^{16}$ cm^{-3}.

[Ans. (*a*) $V_{bi} = 0.772$ V, $x_n = 0.3085\ \mu$m, $x_p = 0.0154\ \mu$m, $W = 0.3240\ \mu$m, $|E_{max}| = 4.77 \times 10^4$ V/cm; (*b*) $V_{bi} = 0.699$ V, $x_n = 0.0596\ \mu$m, $x_p = 0.4469\ \mu$m, $W = 0.5064\ \mu$m, $|E_{max}| = 2.76 \times 10^4$ V/cm]